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Threshold-dependent Occupancy Control Schemes for 3GPP's ARQ

3GPP의 ARQ를 위한 threshold에 의존하는 점유량 조절 방식

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Abstract

3GPP RLC protocol specification adopted a window-controlled selective-repeat ARQ scheme for provisioning reliable data transmission. Inevitably, the re-ordering issue arises in the 3GPP's ARQ since it belongs to the selective-repeat ARQ clan. A long re-ordering time results in the degradation of throughput and delay performance, and may invoke the overflow of the re-ordering buffer. Also, the re-ordering time must be regulated to meet the requirements of some services which are both loss-sensitive and delay-sensitive. In the 3GPP's ARQ, we may deflate the occupancy of the re-ordering buffer by reducing the window size and/or length of the status report period. Such a decrease, however, deteriorates the throughput and delay performance and encroaches the resource of the reverse channel. Aiming at reducing the occupancy at the re-ordering buffer while suppressing the degradation of throughput and delay performance, we propose threshold-dependent occupancy control schemes, identified as post-threshold and pre-threshold schemes, as supplements to the 3GPP's ARQ. For judging the effectiveness of the proposed schemes, we investigate peak occupancy, maximum throughput and average delay in the practical environment involving fading channels. From the simulation results, we observe that the proposed schemes invoke the performance trade-off between occupancy and throughput in general. Also, we reveal that the post-threshold scheme is able to improve the throughput and delay performance of the ordinary 3GPP's ARQ without inflating the occupancy of the re-ordering buffer.

요 약

3GPP는 RLC 프로토콜 명세서에서 신뢰할 수 있는 데이타 전송을 위해 window에 의해 조절되는 selective-repeat ARQ 방식을 채택하였다. 3GPP의 ARQ는 selective-repeat ARQ 부류에 속하므로 재정렬 문제가 불가피하게 야기된다. 긴 재정렬 시간은 throughput 및 지연 성능의 열화를 빚어내고 재정렬 버퍼의 범람을 불러올 수 있다. 또한 데이타의 상실 및 지연에 모두 민감한 서비스의 요구 조건을 수용하기 위해 재정렬 시간은 반드시 통제되어야 한다. 3GPP ARQ에서 window의 크기나 상태 보고 주기를 줄여 재정렬 버퍼의 점유량을 감소시킬 수 있다. 이로 인해 throughput 및 지연 성능이 저하되고 역방향 채널의 자원이 잠식된다. 재정렬 버퍼의 점유량을 줄이는 동시에 throughput 및 지연 성능의 열화를 억제하기 위한 방안으로 본 논문에서는 post-threshold 방식과 pre-threshold 방식이라는 threshold에 의존하는 점유량 조절 방식을 제안한다. 제안한 방식의 효과성을 판단하기 위해 fading 채널 등 실제적인 환경에서 최고 점유량, 최대 throughput, 평균 지연을 조사한다. 모의 실험 결과로부터 제안한 방식이 점유량과 throughput 간에 trade-off를 불러옴을 관찰한다. 또한 post-threshold 방식은 3GPP의 ARQ와 비교하여 재정렬 버퍼의 점유량을 증가시키지 않고 throughput 및 지연 성능을 향상시킬 수 있음을 확인한다.

Keywords: *3GPP*, *ARQ*, *re-ordering*, *occupancy*, *threshold*

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Ⅰ. Introduction

In 1998, the 3rd Generation Partnership Project (3GPP) was founded with the aim of providing globally applicable technical specifications for a third generation mobile system based on wideband code division multiple access (W-CDMA) technologies [1]. Since then, the 3GPP has released a number of 3GPP specifications including 3GPP radio link control (RLC) specification [2]. For provisioning reliable data transmission, the 3GPP RLC specification adopted a window-controlled selective-repeat automatic repeat request (ARQ) scheme [3]. In conjunction with the 3GPP's ARQ, two types of protocol data units (PDU's) identified as acknowledged mode DATA PDU and STATUS PDU are basically used. Also, a distinctive window (a time-varying set of consecutively numbered DATA PDU's) is formed at each of the transmitting and receiving stations. The outline of the 3GPP's ARQ is as follows: The transmitting station sends a DATA PDU if the DATA PDU belongs to its current window. The receiving station then inspects the DATA PDU for errors at the physical layer. If no error is detected, the receiving station identifies the sequence number of the DATA PDU at the RLC layer. Then, the receiving station accepts the DATA PDU if the DATA PDU belongs to the current window of the receiving station. Otherwise, the receiving station rejects the DATA PDU. The receiving station also reports a list of the currently accepted DATA PDU's to the transmitting station. For this purpose, the receiving station records such a list on a STATUS PDU (by means of LIST, Bitmap or RLIST) and sends the STATUS PDU, for example, periodically. Upon reception of a STATUS PDU, the transmitting station identifies negatively acknowledged DATA PDU's and sends them again to the receiving station.

Since the 3GPP's ARQ is a member of selective-repeat ARQ clan, the re-ordering issue arises inevitably. In the 3GPP's ARQ, the receiving station is not guaranteed to receive DATA PDU's in order. Thus, the receiving station must re-order DATA PDU's, which necessitates a buffer to temporarily store disordered DATA PDU's. A long re-ordering time results in the degradation of throughput and delay performance, and may invoke the overflow of the re-ordering buffer [4]. Also, the re-ordering time must be regulated to meet the requirements of some services which are both loss-sensitive and delay-sensitive [5]. In the 3GPP's ARQ, the occupancy of the re-ordering buffer as well as the re-ordering time can be controlled by adjusting the window size and length of the status report period. By reducing the window size and/or length of the status report period, we can deflate the occupancy of the re-ordering buffer. Such a decrease in window size, however, deteriorates the throughput and delay performance. Furthermore, frequent reports of the acceptance status causes the encroachment on the resource of the reverse channel. (In section 4, figures 1 to 6 illustrate the effect of the window size and length of the status report period on the occupancy, throughput and delay performance.)

Aiming at reducing the occupancy at the re-ordering buffer while suppressing the degradation of throughput and delay performance, we propose threshold-dependent occupancy control schemes identified as post-threshold and pre-threshold schemes. These two schemes are based on the idea of combining a go-back-N ARQ with a selective-repeat ARQ. Upon reception of a disordered PDU, the receiving station rejects it in go-back-N ARQ schemes. Consequently, the receiving station has no disordered PDU to re-order at any moment. Thus, the occupancy of the re-ordering buffer may be reduced by a properly combined ARQ scheme. In the proposed occupancy control schemes, we employ a threshold. Specifically, a threshold is created in the receiving station's window. Once no error is detected in a received DATA PDU, the receiving station examines the sequence number of the DATA PDU in conjunction with the threshold. In the post-threshold scheme, the DATA PDU is accepted as in the ordinary 3GPP's ARQ unless the DATA PDU is later than the threshold. However, in case that the DATA PDU is later than the threshold, the DATA

PDU is accepted only if all DATA PDU's which are later than the threshold and earlier than the DATA PDU have been already accepted. On the other hand, the pre-threshold scheme treats the DATA PDU as the ordinary 3GPP's ARQ if the DATA PDU is later than the threshold. In case that the DATA PDU is not later than the threshold, however, the DATA PDU is accepted only if all DATA PDU's which are earlier than the DATA PDU have been already accepted. As described above, the post-threshold and pre-threshold schemes behave symmetrically with respect to the threshold. The post-threshold scheme handles a DATA PDU which is later than the threshold as similarly as go-back-N ARQ, while the pre-threshold scheme does a DATA PDU which is earlier than the threshold.

In the threshold-dependent occupancy control schemes, we expect that the tight condition of DATA PDU acceptance deflates the occupancy of the re-ordering buffer. In turn, the throughput and delay performance may deteriorate due to the tight acceptance condition. Using a simulation method, we thus investigate the peak occupancy, maximum throughput and average delay, and examine the effectiveness of the proposed schemes. In particular, we represent the forward and reverse channels between transmitting and receiving stations as independent two-state Gilbert channels, and import fading characteristics of wireless links on them [5][6].

In section 2, we present the post-threshold and pre-threshold schemes. In section 3, we describe the simulation environment and performance measures to evaluate the threshold-dependent occupancy control schemes. Section 4 is devoted to the simulation results illustrating the occupancy, throughput and delay performance of the proposed schemes.

II. Threshold-dependent Occupancy Control Schemes

In this section, we describe the threshold-dependent occupancy control schemes. These schemes are supplements to the 3GPP's ARQ. We first briefly review the ordinary 3GPP's ARQ and then describe the post-threshold and pre-threshold schemes.

2.1 Ordinary 3GPP's ARQ

In the ordinary 3GPP's ARQ, the transmitting station is logically equipped with entry and re-entry buffers. When a new DATA PDU arrives at the transmitting station, the transmitting station immediately stores the DATA PDU at the bottom of the entry buffer and endows it with a sequence number. When the transmitting station receives a STATUS PDU from the receiving station, the transmitting station identifies negatively acknowledged DATA PDU's. Then, the transmitting station sequentially stores these DATA PDU's at the bottom of the re-entry buffer. When the transmitting station is ready to send a DATA PDU, the transmitting station chooses a DATA PDU from entry or re-entry buffers. The DATA PDU's at the re-entry buffer are always granted higher priority over the ones at the entry buffer. Thus, the transmitting station chooses the DATA PDU at the head of the entry buffer only when the re-entry buffer is empty.

Upon reception of a DATA PDU, the receiving station inspects the DATA PDU for errors at the physical layer. If no error is detected on the DATA PDU, the receiving station identifies the sequence number of the DATA PDU at the RLC layer. A time-varying set of DATA PDU's, called window, is formed at the receiving station. Suppose that W is prescribed for the window size. At time $t \in (0, \infty)$, let $M(t)+1$ be the sequence number of the DATA PDU that the receiving station expects to receive. Then, the window at time t is defined as

$$\Omega(t) = \{M(t)+1, \cdots, M(t)+W\}. \tag{1}$$

Suppose that the receiving station receives a DATA PDU at time t. Assume that no error is detected on the DATA PDU and the sequence number of the DATA PDU is identified as k. Then, the DATA

PDU is either accepted or rejected according to the sequence number k. Let $\Lambda(t)$ denote the set of DATA PDU's which reside in the re-ordering buffer. Hereafter, we call $\Lambda(t)$ the occupant set. If the DATA PDU is accepted, the occupant set may be changed to $\Lambda(t+\Delta t)$. Also, the window may be updated to $\Omega(t+\Delta t)$.

(1) Suppose that $k\in\{1,\cdots,M(t)\}$. Then the DATA PDU is rejected.

(2) Suppose that $k=M(t)+1$ and $M(t)+2\in\Lambda(t)$. Then the DATA PDU is accepted. Define

$$j^*=\max\{j\in\{2,\cdots,W\}: \{M(t)+2,\cdots,M(t)+j\}\subset\Lambda(t)\}. \quad (2)$$

Then, the window is updated to $\Omega(t+\Delta t)$ such that $M(t+\Delta t)=M(t)+j^*$. The occupant set is also changed to $\Lambda(t+\Delta t)=\Lambda(t)\setminus\{1,\cdots,j^*\}$.

(3) Suppose that $k=M(t)+1$ and $M(t)+2\notin\Lambda(t)$. Then, the DATA PDU is accepted. The window is updated to $\Omega(t+\Delta t)$ such that $M(t+\Delta t)=M(t)+1$. However, the occupant set is not changed, i.e. $\Lambda(t+\Delta t)=\Lambda(t)$.

(4) Suppose that $k\in\{M(t)+2,\cdots,M(t)+W\}\setminus\Lambda(t)$. Then, the DATA PDU is accepted. The occupant set is changed to $\Lambda(t+\Delta t)=\Lambda(t)\cup\{k\}$.

(5) Suppose that $k\in\Lambda(t)$. Then, the DATA PDU is rejected.

(6) Suppose that $k\in\{M(t)+W+1,M(t)+W+2,\cdots\}$. Then, the DATA PDU is rejected.

The receiving station records the list of currently accepted DATA PDU's on a STATUS PDU. Through the reverse channel, the receiving station then sends STATUS PDU's periodically.

2.2 Post-threshold Scheme

In the post-threshold scheme, a relative threshold $\nu_{POST}\in\{0,\cdots,W\}$ is prescribed at the receiving station. At each time t, the threshold is defined as $M(t)+\nu_{POST}$. Suppose that the receiving station received a DATA PDU and detected no error in it. Then, the receiving station examines whether the DATA PDU belongs to the current window. If it does, the receiving station accepts the DATA PDU in the ordinary 3GPP's ARQ. In the post-threshold scheme, however, the receiving station examines again the sequence number of the DATA PDU belonging to the current window in relation to the threshold. The DATA PDU is accepted unless the DATA PDU is later than the threshold. However, in case that the DATA PDU is later than the threshold, the DATA PDU is accepted only if all DATA PDU's which are later than the threshold as well as earlier than the DATA PDU have been already accepted.

The complete algorithm of the post-threshold scheme is as follows: Suppose that the receiving station receives a DATA PDU at time t. Assume that no error is detected in the DATA PDU and the sequence number of the DATA PDU is identified as k. In the following, we assume that $W\in\{4,5,\cdots\}$ and $\nu_{POST}\in\{2,\cdots,W-2\}$.

(1) Suppose that $k\in\{1,\cdots,M(t)\}$. Then the DATA PDU is rejected.

(2) Suppose that $k=M(t)+1$ and $M(t)+2\in\Lambda(t)$. Then the DATA PDU is accepted. The window is updated to $\Omega(t+\Delta t)$ such that $M(t+\Delta t)=M(t)+j^*$, where j^* is defined in (2). The occupant set is also changed to $\Lambda(t+\Delta t)=\Lambda(t)\setminus\{1,\cdots,j^*\}$.

(3) Suppose that $k=M(t)+1$ and $M(t)+2\notin\Lambda(t)$. Then, the DATA PDU is accepted. The window is updated to $\Omega(t+\Delta t)$ such that $M(t+\Delta t)=M(t)+1$. However, the occupant set is not changed, i.e. $\Lambda(t+\Delta t)=\Lambda(t)$.

(4) Suppose that $k\in\{M(t)+2,\cdots,M(t)+\nu_{POST}\}\setminus\Lambda(t)$. Then, the DATA PDU is accepted. The occupant set is changed to $\Lambda(t+\Delta t)=\Lambda(t)\cup\{k\}$.

(5) Suppose that $k=M(t)+\nu_{POST}+1$ and $k\notin\Lambda(t)$. Then, the DATA PDU is accepted. The occupant set is changed to $\Lambda(t+\Delta t)=\Lambda(t)\cup\{k\}$.

(6) Suppose that $k\in\{M(t)+\nu_{POST}+2,\cdots,M(t)+W\}\setminus\Lambda(t)$ and $k-1\in\Lambda(t)$. Then, the DATA PDU is accepted. The occupant set is changed to $\Lambda(t+\Delta t)=\Lambda(t)\cup\{k\}$.

(7) Suppose that $k\in\{M(t)+\nu_{POST}+2,\cdots,M(t)+W\}\setminus\Lambda(t)$ and $k-1\notin\Lambda(t)$. Then, the DATA PDU is rejected.

(8) Suppose that $k\in\Lambda(t)$. Then, the DATA PDU is

rejected.

(9) Suppose that $k \in \{M(t)+W+1, M(t)+W+2, \cdots\}$. Then, the DATA PDU is rejected.

2.3 Pre-threshold Scheme

In the pre-threshold scheme, a relative threshold $\nu_{PRE} \in \{0, \cdots, W\}$ is prescribed at the receiving station. At each time t, the threshold is defined as $M(t)+\nu_{PRE}$. Suppose that the receiving station received a DATA PDU and detected no error in it. Then, the receiving station examines whether the DATA PDU belongs to the current window. If it does, the receiving station accepts the DATA PDU in the ordinary 3GPP's ARQ. In the pre-threshold scheme, however, the receiving station examines again the sequence number of the DATA PDU belonging to the current window in relation to the threshold. The receiving station accepts the DATA PDU if the DATA PDU is later than the threshold. In case that the DATA PDU is not later than the threshold, however, the DATA PDU is accepted only if all DATA PDU's which are earlier than the DATA PDU have been already accepted.

The complete algorithm of the pre-threshold scheme is as follows: Suppose that the receiving station receives a DATA PDU at time t. Assume that no error is detected in the DATA PDU and the sequence number of the DATA PDU is identified as k. In the following, we assume that $W \in \{4, 5, \cdots\}$ and $\nu_{PRE} \in \{2, \cdots, W-2\}$.

(1) Suppose that $k \in \{1, \cdots, M(t)\}$. Then the DATA PDU is rejected.

(2) Suppose that $k = M(t)+1$. Then the DATA PDU is accepted. The window is updated to $\Omega(t+\Delta t)$ such that $M(t+\Delta t) = M(t)+1$. However, the occupant set is not changed, i.e. $\Lambda(t+\Delta t) = \Lambda(t)$.

(3) Suppose that $k \in \{M(t)+\nu_{PRE}+1, \cdots, M(t)+W\} \setminus \Lambda(t)$. Then, the DATA PDU is accepted. The occupant set is changed to $\Lambda(t+\Delta t) = \Lambda(t) \cup \{k\}$.

(4) Suppose that $k \in \Lambda(t)$. Then, the DATA PDU is rejected.

(5) Suppose that $k \in \{M(t)+W+1, M(t)+W+2, \cdots\}$. Then, the DATA PDU is rejected.

III. Simulation Environment and Performance Measures

In this section, we describe the environment in which we evaluate the performance of the threshold-dependent occupancy control schemes. Also, we present the measures which are employed to evaluate the threshold-dependent occupancy control schemes.

3.1 Overview

The transmitting station sends a DATA PDU through the forward channel, while the receiving station sends a STATUS PDU across the reverse channel. Both of the forward and reverse channels are slotted. Also, the forward channel is well synchronized with the reverse channel. The transmitting station is allowed to send at most a single DATA PDU during a slot. (The slot duration time is denoted by τ.) In addition, each delivery of a DATA PDU always starts at the beginning of a slot. When the receiving station receives a DATA PDU, it first inspects the DATA PDU for errors (at the physical layer). The receiving station then perfectly detects errors, if any. The length of a STATUS PDU is relatively short compared with the length of a DATA PDU. The receiving station sends STATUS PDU's only periodically, where the length of the status report period, denoted by σ, is an integral multiple of slot duration time. Between the transmitting and receiving stations, the propagation delay is negligibly short.

3.2 DATA PDU Arrival

At the transmitting station, the sequence of DATA PDU arrival times is a Bernoulli point process. Let X_n denote the number of new DATA PDU's that arrive in the nth slot for $n \in \{1, 2, \cdots\}$. Then, $\{X_n, n=1, 2, \cdots\}$ is an independent and identically distributed sequence such that $P(X_n=1) = \lambda \in [0, \infty]$

and $P(X_n=0)=1-\lambda$ for all $n\in\{1,2,\cdots\}$. In addition, we assume that every new DATA PDU arrives at the end of a slot. Let $N((0,t])$ denote the number of new DATA PDU's arriving at the transmitting station in $(0,t]$. Define the DATA PDU arrival rate to be $\lim_{n\to\infty} N((0,n\tau])/n$. Then, the DATA PDU arrival rate is equal to λ.

3.3 Forward and Reverse Channels

Between the peers of RLC layer at the transmitting and receiving stations, the forward and reverse channels are independent two-state Gilbert channels [5][6]. For $n\in\{1,2,\cdots\}$, let $U_n\in\{0,1\}$ and $V_n\in\{0,1\}$ respectively indicate the necessary occurrence of errors in the nth slot on the forward and reverse channels, i.e. the event that $U_n=1$ ($V_n=1$) implies that errors definitely occur if a DATA (STATUS) PDU is sent in the nth slot on the forward (reverse) channel. Then, the sequences $\{U_n, n=1,2,\cdots\}$ and $\{V_n, n=1,2,\cdots\}$ are independent Markov chains on the state space $\{0,1\}$. Let f_F and f_R denote the initial masses and let $p_F: \{0,1\}^2\to(0,1)$ and $p_R: \{0,1\}^2\to(0,1)$ be the transition probability functions of the Markov chains, respectively. Then, from the stationary equations, the steady state mass for $\{U_n, n=1,2,\cdots\}$ is obtained as

$$\begin{aligned} g_F(0) &= \lim_{n\to\infty} P(U_n=0) \\ &= \frac{p_F(1,0)}{p_F(0,1)+p_F(1,0)} \\ g_F(1) &= \lim_{n\to\infty} P(U_n=1) \\ &= \frac{p_F(0,1)}{p_F(0,1)+p_F(1,0)}\,. \end{aligned} \tag{3}$$

By substituting p_R for p_F in (8), we also have the steady state mass for $\{V_n, n=1,2,\cdots\}$, denoted by g_R. Define the error rates on the forward and reverse channels to be $\lim_{n\to\infty}\frac{1}{n}\sum_{j=1}^{n} U_j$ and $\lim_{n\to\infty}\frac{1}{n}\sum_{j=1}^{n} V_j$, respectively. Then, the error rates on the forward and reverse channels, denoted by ε and δ are

$$\begin{aligned} \varepsilon &= g_F(1) \\ \delta &= g_R(1)\,. \end{aligned} \tag{4}$$

An error burst on the forward (reverse) channel is a period consisting of consecutive slots in each of which errors necessarily occur. Set

$$\begin{aligned} F_1^F &= \min\{n\in\{1,2,\cdots\}: X_n=1\} \\ F_{k+1}^F &= \min\{n\in\{F_k^F+1, F_k^F+2,\cdots\}: \\ &\qquad U_n=1, U_{n-1}=0\} \\ L_k^F &= \min\{n\in\{F_k^F+1, F_k^F+2,\cdots\}: \\ &\qquad U_n=0\}-1 \end{aligned} \tag{5}$$

for $k\in\{1,2,\cdots\}$. Then, the kth error burst on the forward channel is defined to be $(\tau(F_k^F-1), \tau L_k^F]$ for $k\in\{1,2,\cdots\}$. Also, the kth error burst on the reverse channel is defined to be $(\tau(F_k^R-1), \tau L_k^R]$, where we define F_k^R and L_k^R as similar as F_k^F and L_k^F by substituting V_n for U_n in (5). Set $G_k^F=L_k^F-F_k^F+1$ and $G_k^R=L_k^R-F_k^R+1$ for $k\in\{1,2,\cdots\}$. Note that the lengths of the kth error burst on the forward and reverse channels are $\tau(L_k^F-F_k^F+1)$ and $\tau(L_k^R-F_k^R+1)$, respectively. Thus, G_k^F and G_k^R are the normalized lengths of the kth error burst on the forward and reverse channels. Then, $\{G_k^F, k=1,2,\cdots\}$ and $\{G_k^R, k=1,2,\cdots\}$ are independent and identically distributed sequences. Also, G_k^F and G_k^R respectively have the geometric distributions with parameters $p_F(1,1)$ and $p_R(1,1)$. Let α and β denote the means of G_k^F and G_k^R. Then, we have

$$\begin{aligned} \alpha &= E(G_k^F) = \frac{1}{1-p_F(1,1)} \\ \beta &= E(G_k^R) = \frac{1}{1-p_R(1,1)}\,. \end{aligned} \tag{6}$$

In the simulation, we set the initial masses to be $f_F(j)=P(U_1=j)=g_F(j)$ and $f_R(j)=P(V_1=j)=g_R(j)$ for $j\in\{0,1\}$. Note that the pairs (ε,α) and (δ,β) construct the Markov chains $\{U_n, n=1,2,\cdots\}$ and $\{V_n, n=1,2,\cdots\}$, respectively.

In the earlier works, attempts were made to reflect the physical properties, (e.g. Doppler frequency and fade margin) of a wireless channel on the two-state Gilbert channel between the peers of RLC layer. By using simulation results on the values of transition probability function p_F, [5] introduced estimates of the pair of error rate (ε) and normalized average length of error burst (α). On the other hand, [6] presented a numerical method to calculate ε and α based on Jakes' model [7], while assuming the channel is not changed during a slot.

Table 1 summarizes the channels employed in the simulation. (We assume that the forward and reverse channels are independent and they have identical characteristics.) In channel 1, we use the values of the error rate (ε and δ) and the average length of error burst (α and β) which are obtained by the numerical method given in [6]. On the other hand, channel 2 involves the simulation-based estimates of ε (δ) and α (β) presented in [5]. Note that channel 3 is a Bernoulli channel.

Table 1. Models for forward and reverse channels.
표 1. 순방향 채널과 역방향 채널의 모형.

channel model	error rate (ε, δ)	average length of error burst (α, β)
channel 1	0.122688	7.736507
channel 2	0.122688	3.078258
channel 3	0.122688	1.398453

3.4 Performance Measures

For the performance evaluation, we use three measures: peak occupancy of the re-ordering buffer, average delay of DATA PDU and maximum normalized throughput.

Recall that τ denotes the slot duration time. Let Y_n denote the number of DATA PDU's residing in the re-ordering buffer at time $n\tau-$, (i.e. $Y_n=|\Lambda(n\tau-)|$). Let Y be a random variable such that $Y_n \xrightarrow{d} Y$ as $n\to\infty$. Then, The peak occupancy is defined as the 99th percentile of Y, denoted by ζ_{99}.

In the simulation, we obtain the samples $Y_1(\omega),\cdots,Y_m(\omega)$ of $Y_1,\cdots,Y_m$ and estimate the peak occupancy by

$$\widehat{\zeta_{99}}=\min\left\{W-1,\ \frac{1}{m}\sum_{n=1}^{m}Y_n(\omega)+3\sqrt{\frac{1}{m}\sum_{n=1}^{m}Y_n(\omega)^2-\left[\frac{1}{m}\sum_{n=1}^{m}Y_n(\omega)\right]^2}\right\}. \qquad (7)$$

Let A_k be the time that the kth DATA PDU arrives at the entry buffer of the transmitting station for $k\in\{1,2,\cdots\}$. Let R_k denote the time that the kth DATA PDU departs from the transmitting station, i.e. the time that the transmitting station confirms the acceptance of the kth DATA PDU by reading a STATUS PDU. Then, the delay of the kth DATA PDU, denoted by D_k is defined as R_k-A_k. Suppose that there exists a random variable D such that $D_k\xrightarrow{d}D$ as $k\to\infty$. Then, the average delay of DATA PDU is defined as $\mu=E(D)$. In the simulation, we obtain the samples $D_1(\omega),\cdots,D_m(\omega)$ of $D_1,\cdots,D_m$ and estimate the average delay by

$$\widehat{\mu}=\frac{1}{m}\sum_{k=1}^{m}D_k(\omega). \qquad (8)$$

Suppose that the transmitting station is saturated, i.e. it always has infinite number of DATA PDU's at the entry buffer. Define H_n to be $sup\{k\in\{1,2,\cdots\}:R_k\le n\tau\}$ for $n\in\{1,2,\cdots\}$. Then, we define the maximum normalized throughput, denoted by η to be $\lim_{n\to\infty}H_n/n$. In the simulation, we obtain the sample $H_m(\omega)$ of H_m and estimate the maximum normalized throughput by

$$\widehat{\eta}=\frac{H_m(\omega)}{m}. \qquad (9)$$

IV. Simulation Results

In this section, we evaluate the occupancy, throughput and delay performance of the threshold-dependent schemes in the simulation environment described in section 3.

Figures 1, 2 and 3 show the effect of the window size on the peak occupancy, maximum throughput and average delay, respectively, in the ordinary 3GPP′s ARQ. In these figures, we set the length of status report period (σ/τ) to be 16 (slot times). In addition, the receiving station in figure 1 is either saturated or loaded with DATA PDU′s by rate 0.8 (DATA PDU′s/slot time). Also, we set the traffic load (λ) in figure 3 to be 0.8 (DATA PDU′s/slot time).

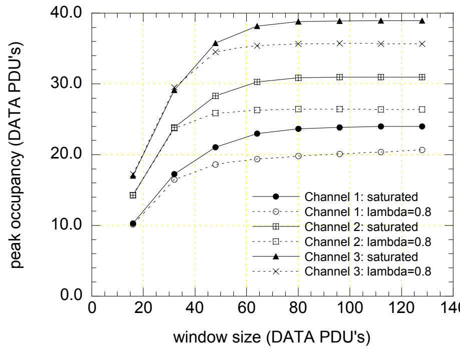

Fig. 1. Peak occupancy $\widehat{\zeta_{\mathfrak{B}}}$ vs. window size W in ordinary 3GPP′s ARQ.
그림 1. 본래의 3GPP ARQ에서 window 크기 W에 따른 최고 점유량 $\widehat{\zeta_{\mathfrak{B}}}$.

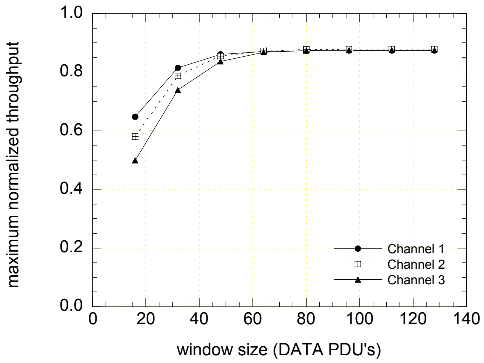

Fig. 2. Maximum normalized throughput $\hat{\eta}$ vs. window size W in ordinary 3GPP′s ARQ.
그림 2. 본래의 3GPP ARQ에서 window 크기 W에 따른 최대 정규화 된 throughput $\hat{\eta}$

In figure 1, we observe that the peak occupancy decreases as the window size decreases. However, figures 2 and 3 show that the maximum throughput decreases and the average delay increases as the window size decreases. Such observation indicates that the improvement of occupancy performance in figure 1 is attained by trading off the throughput and delay performance.

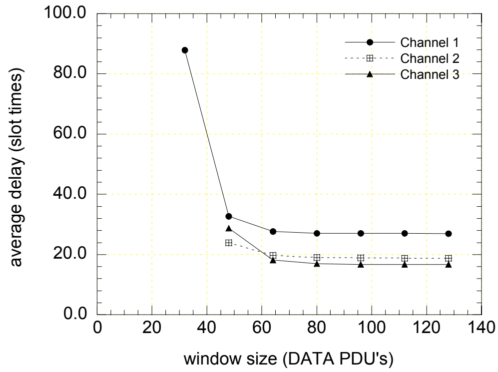

Fig. 3. Average delay $\hat{\mu}$ vs. window size W in ordinary 3GPP′s ARQ.
그림 3. 본래의 3GPP ARQ에서 window 크기 W에 따른 평균 지연 시간 $\hat{\mu}$

In figure 1, we notice that the faster fading channel incurs the higher peak occupancy. (Note that channel 3 is the fastest fading channel among the three channels given in table 1.) On the other hand, figure 3 shows the average delay is lower at the faster fading channel when the window size is large enough. We surmise that the following factors bring about such phenomena: When a faster fading channel is involved, disordered DATA PDU′s are more uniformly distributed at the re-ordering buffer and these are less likely to depart from the re-ordering buffer at a window update. Meanwhile, the slower fading channel incurs the larger variance of the time for the transmitting station to complete the service for a DATA PDU, which results in the longer average delay.

Figures 4, 5 and 6 show the effect of the length of status report period on the peak occupancy, maximum throughput and average delay, respectively, in the ordinary 3GPP′s ARQ. In these figures, we set the window size (W) to be 128 (DATA PDU′s). In addition, the receiving station in figure 4 is either saturated or loaded with DATA PDU′s by rate 0.6

(DATA PDU's/slot time). Also, we set the traffic load (λ) in figure 6 to be 0.6 (DATA PDU's/slot time).

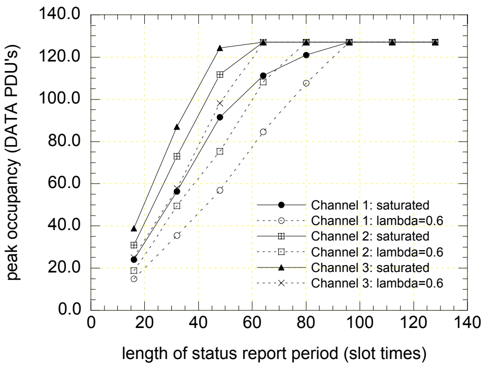

Fig. 4. Peak occupancy $\widehat{\zeta_{\wp}}$ vs. length of status report period σ/τ in ordinary 3GPP's ARQ.
그림 4. 본래의 3GPP ARQ에서 상태 보고 주기의 길이 σ/τ에 따른 최고 점유량 $\widehat{\zeta_{\wp}}$.

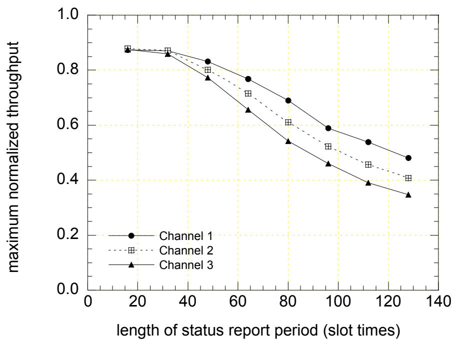

Fig. 5. Maximum normalized throughput $\hat{\eta}$ vs. length of status report period σ/τ in ordinary 3GPP's ARQ.
그림 5. 본래의 3GPP ARQ에서 상태 보고 주기의 길이 σ/τ에 따른 최대 정규화 된 throughput $\hat{\eta}$

In figure 4, we observe that the peak occupancy decreases as the length of status report period decreases. In figures 5 and 6, we also notice that the maximum throughput increases and the average delay decreases as the length of status report period decreases. As a result, these figures confirm that we are able to improve all of the occupancy, throughput and delay performance by shortening the length of status report period. As addressed in section 1, however, we note that such a decrease in status report period encroaches the resource of the reverse channel.

Figures 7, 8 and 9 show the effect of the relative threshold on the peak occupancy, maximum throughput and average delay, respectively, in the post-threshold scheme. In these figures, we set the window size (W) and the length of status report period (σ/τ) to be 128 (DATA PDU's) and 32 (slot times), respectively. In addition, the receiving station

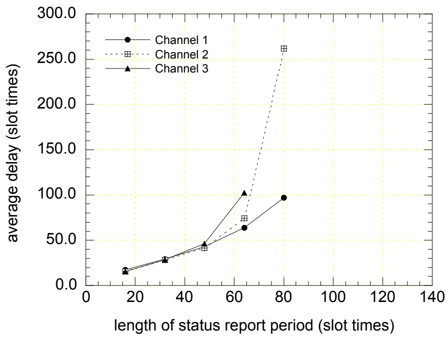

Fig. 6. Average delay $\hat{\mu}$ vs. length of status report period σ/τ in ordinary 3GPP's ARQ.
그림 6. 본래의 3GPP ARQ에서 상태 보고 주기의 길이 σ/τ에 따른 평균 지연 시간 $\hat{\mu}$

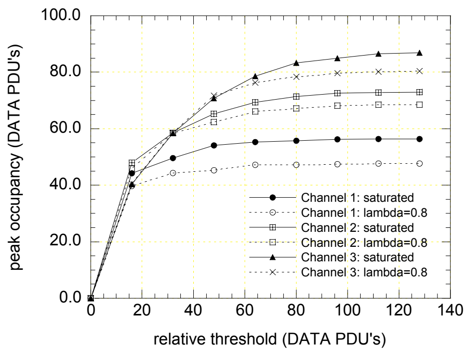

Fig. 7. Peak occupancy $\widehat{\zeta_{\wp}}$ vs. relative threshold ν_{POST} in post-threshold scheme.
그림 7. Post-threshold 방식에서 상대적 threshold ν_{POST}에 따른 최고 점유량 $\widehat{\zeta_{\wp}}$.

in figure 7 is either saturated or loaded with DATA PDU's by rate 0.8 (DATA PDU's/slot time). Also, we set the traffic load (λ) in figure 9 to be 0.8 (DATA PDU's/slot time).

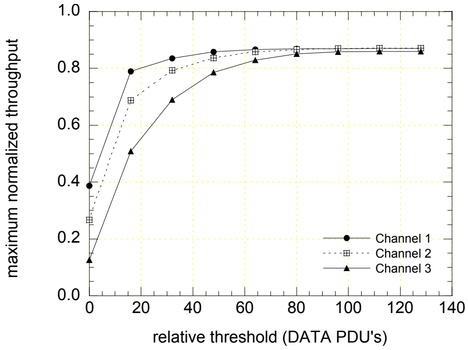

Fig. 8. Maximum normalized throughput $\hat{\eta}$ vs. relative threshold ν_{POST} in post-threshold scheme.
그림 8. Post-threshold 방식에서 상대적 threshold ν_{POST}에 따른 최대 정규화 된 throughput $\hat{\eta}$

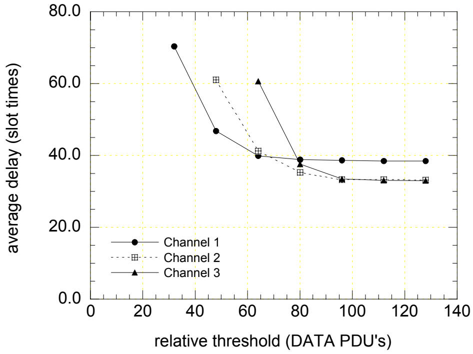

Fig. 9. Average delay $\hat{\mu}$ vs. relative threshold ν_{POST} in post-threshold scheme.
그림 9. Post-threshold 방식에서 상대적 threshold ν_{POST}에 따른 평균 지연 시간 $\hat{\mu}$

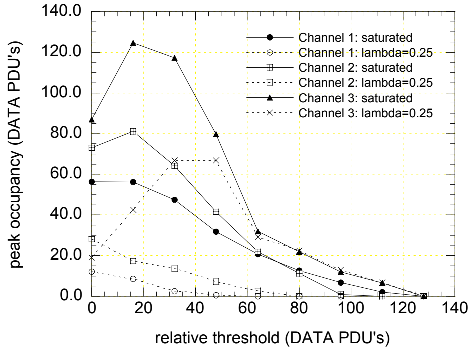

Fig. 10. Peak occupancy $\widehat{\xi_{\wp}}$ vs. relative threshold ν_{PRE} in pre-threshold scheme.
그림 10. Pre-threshold 방식에서 상대적 threshold ν_{PRE}에 따른 최고 점유량 $\widehat{\xi_{\wp}}$.

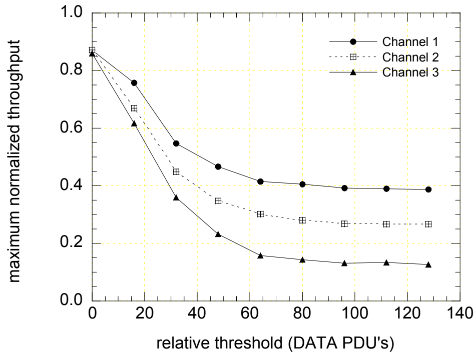

Fig. 11. Maximum normalized throughput $\hat{\eta}$ vs. relative threshold ν_{PRE} in pre-threshold scheme.
그림 11. Pre-threshold 방식에서 상대적 threshold ν_{PRE}에 따른 최대 정규화 된 throughput $\hat{\eta}$

In figure 7, we observe that the peak occupancy increases as the relative threshold approaches the window size (irrelevantly to channel characteristics and traffic load). In figures 8 and 9, we also notice that the maximum throughput increases and the average delay decreases as the relative threshold inc reases. From these figures, we conclude that the change of relative threshold invokes a performance trade-off between occupancy and throughput (and delay as well).

Figures 10, 11 and 12 show the effect of the relative threshold on the peak occupancy, maximum throughput and average delay, respectively, in the pre-threshold scheme. In these figures, we set the window size (W) and the length of status report period (σ/τ) to be 128 (DATA PDU's) and 32 (slot times), respectively. In addition, the receiving station in figure 10 is either saturated or loaded with DATA PDU's by rate 0.25 (DATA PDU's/slot time). Also, we set the traffic load (λ) in figure 12 to be 0.25 (DATA PDU's/slot time).

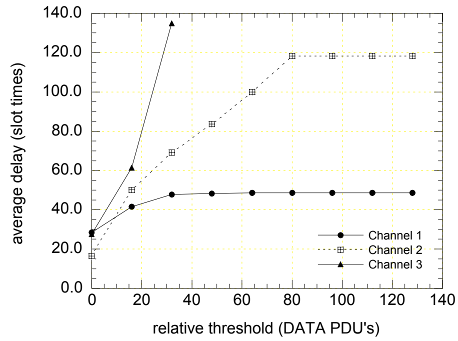

Fig. 12. Average delay $\hat{\mu}$ vs. relative threshold ν_{PRE} in pre-threshold scheme.

그림 12. Pre-threshold 방식에서 상대적 threshold ν_{PRE}에 따른 평균 지연 시간 $\hat{\mu}$

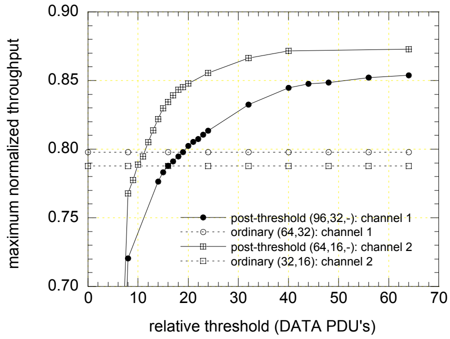

Fig. 13. Maximum normalized throughput $\hat{\eta}$ vs. relative threshold ν_{POST} in post-threshold scheme and ordinary 3GPP's ARQ.

그림 13. Post-threshold 방식과 본래의 3GPP ARQ에서 상대적 threshold ν_{POST}에 따른 최대 정규화된 throughput $\hat{\eta}$

Contrary to the post-threshold scheme, we observe that the pre-threshold scheme does not produce a monotonic curve of the peak occupancy with respect to the relative threshold. Especially when the relative threshold is not large enough, the pre-threshold scheme rather incurs the worse occupancy performance than the ordinary 3GPP's ARQ (where the relative threshold is equal to 0). In the pre-threshold scheme, we note that a DATA PDU earlier than the threshold can be accepted only if it is the earliest DATA PDU that the receiving station expects to receive, and a single DATA PDU is allowed to depart from the re-ordering buffer whenever the window is updated. The pre-threshold scheme tightly controls the acceptance of a DATA PDU. However, the tight control has a side-effect that a small number of DATA PDU's may depart from the re-ordering buffer at a window update. When the relative threshold is not large enough, the dominance of the side-effect results in the higher peak occupancy than the one of the ordinary 3GPP's ARQ. In figures 11 and 12, we observe that the maximum throughput decreases and the average delay increases as the relative threshold increases. Thus, the pre-threshold scheme trades off the throughput and delay performance against the occupancy performance (when the relative threshold is large).

In figures 13, 14 and 15, we compare the post-threshold scheme with the ordinary 3GPP's ARQ in maximum throughput, average delay and peak occupancy, respectively. Figure 13 shows the maximum normalized throughput with respect to the relative threshold. In this figure, the throughput performance of the post-threshold scheme in which the window size W = 96 and the length of status report period σ/τ = 32 is evaluated in comparison with the one of the ordinary 3GPP's ARQ in which W = 64 and σ/τ = 32. We notice that the post-threshold scheme invokes the higher maximum throughput than the ordinary 3GPP's ARQ if the relative threshold is greater than 18. Also, we observe that the post-threshold scheme with W = 64 and σ/τ = 16 produces the higher maximum throughput than the ordinary 3GPP's ARQ with W = 32 and σ/τ = 16 if the relative threshold is greater than 9.

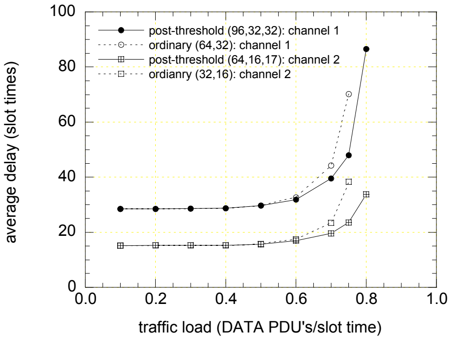

Fig. 14. Average delay $\widehat{\mu}$ vs. traffic load λ in post-threshold scheme and ordinary 3GPP's ARQ.
그림 14. Post-threshold 방식과 본래의 3GPP ARQ에서 트래픽 부하 λ에 따른 평균 지연 시간 $\widehat{\mu}$

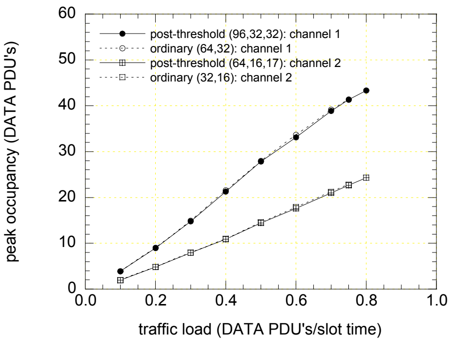

Fig. 15. Peak occupancy $\widehat{\xi_{\wp}}$ vs. traffic load λ in post-threshold scheme and ordinary 3GPP's ARQ.
그림 15. Post-threshold 방식과 본래의 3GPP ARQ에서 트래픽 부하 λ에 따른 최고 점유량 $\widehat{\xi_{\wp}}$.

In figures 14 and 15, we investigate the average delay and peak occupancy of the four schemes summarized in table 2. In figure 14, we observe that scheme 1 exhibits the lower average delay than scheme 2. Also, scheme 3 shows the lower average delay than scheme 4. In figure 15, we notice that scheme 1 (scheme 3) invokes the slightly lower peak occupancy than scheme 2 (scheme 4). Recall that we can increase the maximum throughput by reducing the window size in the 3GPP's ARQ. However, such a reduction leads to the increase in peak occupancy. On the other hand, from the observation on these figures, we conclude that the post-threshold scheme is able to improve the throughput and delay performance without inflating the occupancy at the re-ordering buffer, and confirm the effectiveness of the post-threshold scheme.

Table 2. Schemes used in figures 14 and 15.
표 2. 그림 14와 15에서 사용된 방식.

scheme	category	window size W	length of status report period σ/τ	relative threshold ν_{POST}
scheme 1	post-threshold scheme	96	32	32
scheme 2	ordinary 3GPP's ARQ	64	32	-
scheme 3	post-threshold scheme	64	16	17
scheme 4	ordinary 3GPP's ARQ	32	16	-

V. Conclusions

3GPP RLC protocol specification adopted a window-controlled selective-repeat ARQ scheme. In the 3GPP's ARQ, re-ordering issue arise inevitably. The re-ordering issue may be resolved by decreasing the window size. Such a decrease, however, incurs the deterioration of the throughput and delay performance. Aiming at reducing the occupancy at the re-ordering buffer as well as suppressing the degradation of throughput and delay performance, we proposed threshold-dependent occupancy control schemes identified as post-threshold and pre-threshold schemes. By imposing a tight condition for the acceptance of a DATA PDU which is earlier (or later) than the threshold, these schemes attempt to reduce the occupancy of the re-ordering buffer. In turn, such a tight acceptance condition may incur the deterioration of throughput and delay performance.

Using a simulation method, we thus investigated the peak occupancy, maximum throughput and average delay in practical environments. From simulation results, we first confirmed that the peak occupancy in the ordinary 3GPP's ARQ is reduced by curtailing the window size or shortening the length of status report period. However, we also noticed that a decrease in window size deteriorates the maximum throughput and average delay. Secondly, we observed that a change of relative threshold generally produces the performance trade-off between occupancy and throughput (and delay as well) in both of the post-threshold and pre-threshold schemes. In the post-threshold scheme, we observed that both of the peak occupancy and maximum throughput decrease monotonically as the relative threshold decreases. On the other hand, we noticed that a higher relative threshold may reduce the maximum throughput and increase the peak occupancy as well. Thirdly, we found that in comparison with the ordinary 3GPP's ARQ, the post-threshold scheme is able to improve the throughput and delay performance without inflating the occupancy of the re-ordering buffer, and confirmed the effectiveness of the post-threshold scheme.

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